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Analysis of Superheater Boiler Tubes Failed through Non-linear Heating

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Abstract

The failure of two superheater tubes (T1&T2) is analyzed in the present investigation. The tubes are fractured perpendicular to tube length and bowed down towards the fire side without any brittleness, as examined through naked eye as well as tensile testing. There is no material loss from inside of tubes. Outer surface wall is thinned down by erosion and corrosion mechanism through fly ash deposits. Subsequently, the non-linear heating leads the catastrophic failure after short service period.

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Keywords: Boiler tube, Corrosion, Erosion, non-linear heating, Hoop stress.

1. Introduction

The boiler tubes are interacted at a harsh environment through inside steam and outside flue gases. One common reason of the boiler tube failure is higher the tube metal temperature than the specified temperature [1]. The temperature rise may be due to the development of scale on the internal and/or external surfaces with prolonged exposure at elevated temperature [2]. Moreover, the scale formation causes non-linear (non-uniform) heating, resulting in the retardation of heat transfer and reduction of the thermal efficiency. The scales are generally complex alkali sulfates, forming from flue gasses. It results in fly ash corrosion at the scale/ metal interface with tube metal temperature ranges of 566 – 732°C [1]. The fly ash corrosion is accelerated owing to the low grade (high ash contents) coals and improper cleaning of tubes during shutdown periods. The aggressive corrosion is highly concerned when the tube wall thickness is reduced at rate of 8 mils/ year or greater [3]. On the other hand, the non-linear (non-uniform) heating prevents the normal heat pick up along the complete length of the tube from inlet to outlet, distorting the tubes to the bowed shape. Therefore, the fly ash corrosion as well as the non-liner (non-uniform) heating affect not only the lifetime of tube materials but also downtime of any thermal power plant. In this

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research, two different types of superheater tubes have been investigated, which are failed at lower than the expected life time.

2. Materials and Methods

The super heater tubes of two categories, T1 (SA210) and T2 (SA213T91) have been collected from a coal fired thermal power plant for present investigation. The chemical compositions and operating conditions of tubes are described in Table-1 and Table-2, respectively. Visual examination was done in naked eyes and photographs were taken by digital camera. Subsequently, the specimens were cut along the cross section of tubes near the failures and away from failure regions for microstructural study. The mounted metallographic specimens were prepared by three steps, grinding up to 1200 grit SiC abrasive paper, cloth polishing up to diamond solution and etching by 2% Nital solution for T1 and Villela's reagent for T2. Microstructural studies were done by a scanning electron microscope (SEM model Hitachi S-3400N). The micro particles deposited on the surface were analyzed by a Thermo NSS-300 energy dispersive spectrometry (EDS) attached with SEM. Tensile properties were evaluated by a universal tensile testing machine of Tinius Olsen (HK25).

Table 1: Chemical composition of investigated tubes

Boiler Tubes	Chemical Composition (in wt%)								
	C	Mn	P	S	Si	Ni	Cr	Mo	Fe
T1	0.29	0.69	0.014	0.034	0.1	-	-	-	Balance
T2	0.1	0.45	0.01	0.01	0.11	0.24	8.71	0.93	Balance

Table 2: Design and service exposed conditions of boiler tubes

Tube No.	P_D (MPa)	T_D (°C)	P_O (MPa)	T_O (°C)	T_F (°C)	Service Exposure (h)	Average Coal Composition
T1	17	429	16	399	545	58880	Fixed Carbon: 30%, Moisture: 3.6%, Volatile Matter: 18%, Ash: 48.3%
T2	18	475	18	450	740	7130	FC-38.1,Ash-42.0,IM-3.2,VM-16.7,CV-4139

P_D= Design Pressure; T_D = Design Temperature; P_O = Operating Pressure; T_O = Operating Temperature; T_F = Flue gas Temperature;

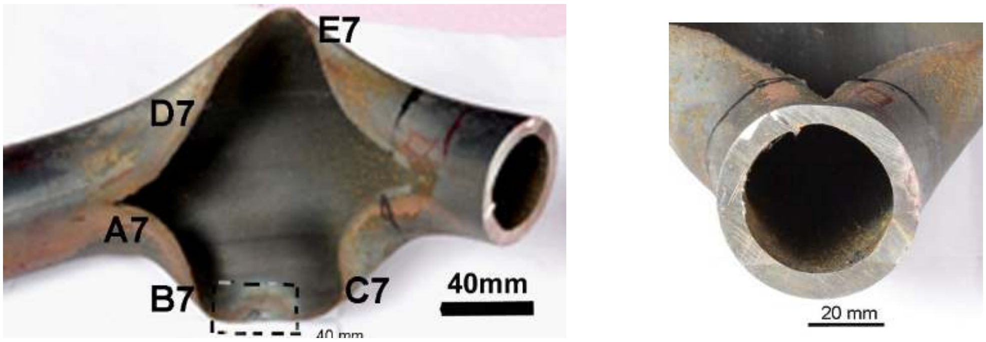
3. Results & Discussions

3.1 Visual Examination

The tube T1 is found to fracture circumferentially (Figs. 1a & b), whereas a square type fish mouth opening of 12 cm long and 12 cm wide along longitudinal direction is observed in tube T2 (Figs. 2a&b). The outer surface wall is locally thinned down at some points. However, there is no material loss at the inner surface wall of the tubes, as shown in the cross-sectional image near the failure (Fig. 1b & 2b). It is interesting to note that the fractured portion of tubeT1 is caved inside (C3 in Fig.1a), but tube thickness has no reduction entire the failure region. The changing color near fish mouth opening of tube T2 is the signs of high temperature flue gas interaction, which is described as hot (fire) side. It is also noticed that the T2 is bent towards hot side. The surface deformation might be due to the continuous erosion by flue gases, resulting in crimping and thinning down the outer surface. It is interesting to note that some regions of tube wall are locally thinned down to 0.8-0.3mm (85-95% of wall thickness).

(a) (b)

Fig. 1 Failed tube T1 (a) close-up view of fractured portion (b) cross sectional view



(a) (b)

Fig. 2 Fish mouth opening in tube T2 (a) longitudinal (b) cross-sectional

3.2 Tensile Properties

Tensile properties of failed boiler tubes explained in Table 3, which comparable to standard tube materials. However, the hoop stress of tube T1 ($\sigma_\theta = \dfrac{pd}{2t}$, where σ_θ is hoop stress, P is internal pressure, t is tube wall thickness and d is tube internal diameter) at the thinnest region is about 2.5 times of UTS value of the steel. It means hoop stress is operative at failed region. Similarly, the hoop stress of tube T2 is near to room temperature yield strength of the material, however, it might be higher than high temperature yielding, resulting in the failure of tube through fish mouth opening.

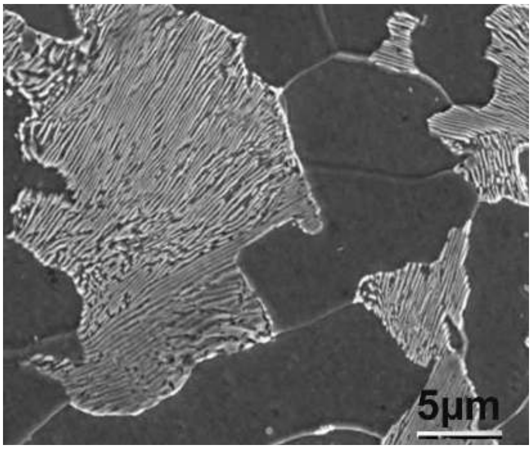
Table 3: Tensile properties and hoop stress of service exposed tubes

Tubes	UTS (MPa)	YS (MPa)	EL (%)	Hoop Stress ($\sigma_\theta = \dfrac{pd}{2t}$,) MPa	
				At initial thickness	At thinnest region
T1	540	394	42	54 (when P= 15.7 MPa, d= 34.5 mm & t= 5 mm)	1177 (when P= 15.7 MPa, d= 34.5 mm & t= 0.23 mm)
T2	604	395	54	47 (when P= 17.65 MPa, d= 33.3 mm & t= 6.3 mm)	367 (when P= 17.65 MPa, d= 33.3 mm & t= 0.8 mm)

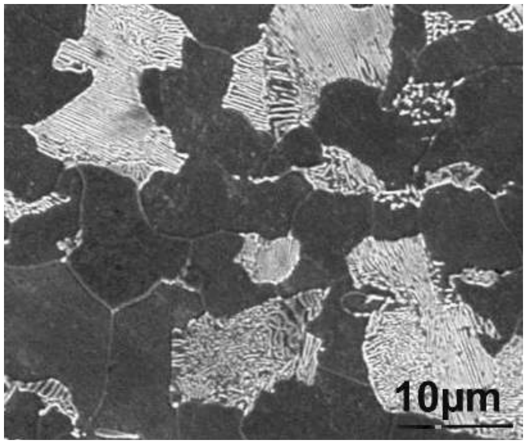
UTS=Ultimate tensile strength, YS=Yield strength, EL= Elongation

3.3 Microstructure Evolution

Fig. 3 shows the microstructures of tube T1, comprising ferrite and pearlite colonies. The pearlite and ferrite are distributed similar way in both near failure and away from failure regions.



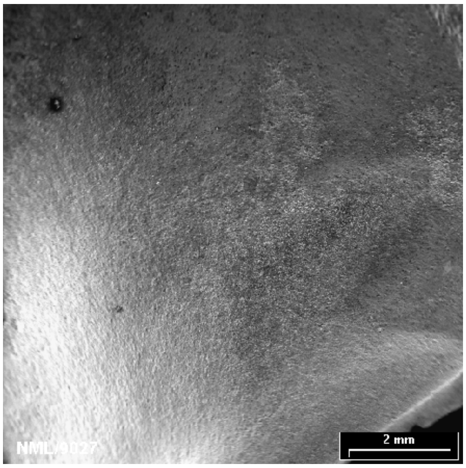
(a)



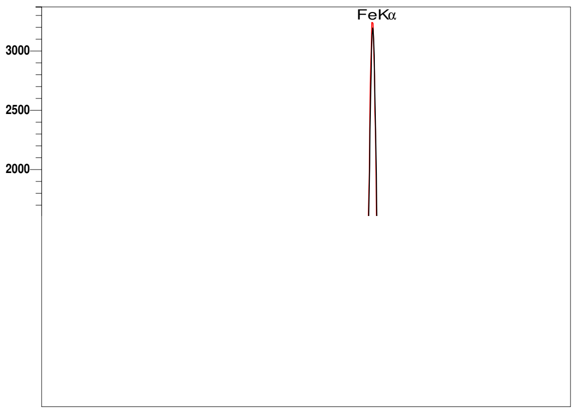
(b)

Fig. 3 SEM images of tubeT1 at (a) away from failure, (b) near failure

Simultaneously, the thinnest failure region (B3 of Fig.1a) is explained as rough region with the presence of fused particles due to coal-ash/fly-ash corrosion and erosion through flue gas (Fig. 4a). It results in localized thinning. The particles are K and Ca based alkali compounds along with some Ti and silica, as confirmed through EDS analysis (Fig. 4b).



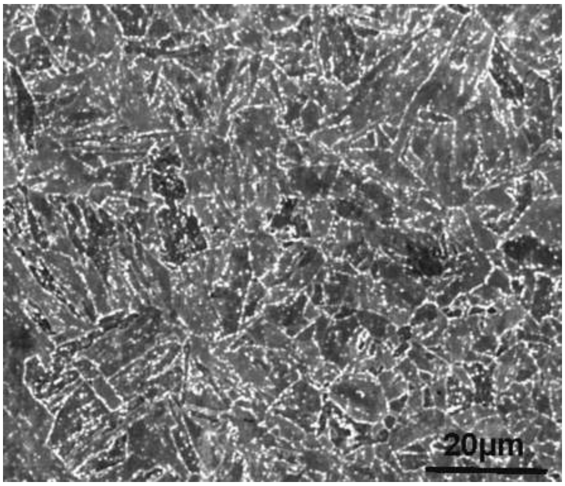
(a)



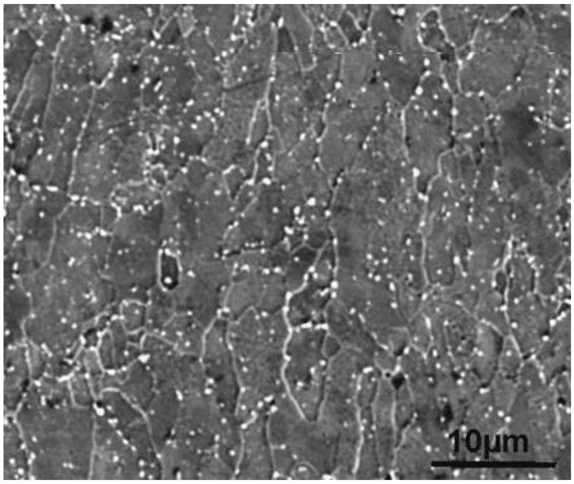
(b)

Fig..4: (a) SEM image of the corroded/eroded area of B3 region (as shown in fig. 1a) in tube T1 and (b) EDS qualitative analysis of surface shown in Fig. 4a

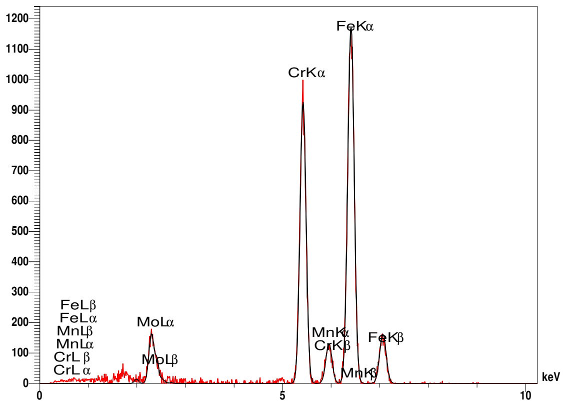
Unlike T1, the microstructure of tube T2 consists of tempered martensite and fine carbides at both away and near failure sites (Figs. 5a &5b). This microstructural changes are due to the effects of Cr and Mo elements in this steel. A large number of fine carbides have been found in the matrix, which are mostly (Cr, Mo) carbide, as explained in EDS analysis of failure region (Fig. 5c).



(a)



(b)

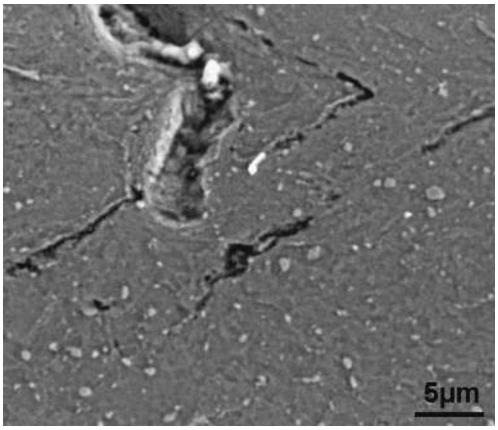


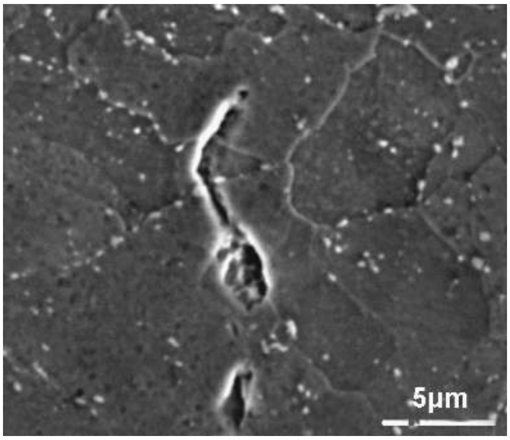
Elements	Wt%
Cr	30.0
Mn	0.19
Fe	64.45
Mo	5.3

(c)

Fig. 5: SEM images of tube T2 showing the regions: (a) away from failure, (b) near failure, (c) EDS analysis of Fig. 5b

Fig. 6 shows the SEM image at the cross sectional area of thin edge (shown as dotted line in Fig. 2a) near failure region of tube T2. A large nos. of voids and cracks has been found at the grain boundaries, and the cracks are propagated through the grain boundaries (Figs. 6 a&b). Moreover, the carbide particles are coarsened in the matrix and grain boundary. The generation of cracks and voids near the thin edge is related to sudden rise of temperature at the failure zone. The non-linear temperature gradient, i.e., the non-uniform temperature distribution, is one of the main reasons for sudden temperature rising in the tubes, preventing normal heat pick up along the complete length of tube from inlet to outlet. Simultaneously, the outer surface thinning of tube- T2 occurs owing to the continuous erosion through flue gases. It is evidenced by thickness reduction of tube T2, but no internal material loss, as shown in Fig. 2b. Similar type of outer surface thinning has also been observed in tube-T1 at very small region (B3 of Fig.1a) which confirms the presence of silicide and oxide particles through EDS analysis. The surface thinning is also related to the hoop stress generation.





(a) (b)

Fig. 6 SEM image of cross sectional area of thin edge region of tube T2 near fracture showing (a) some voids and (b) crack propagation.

Therefore, both tubes initially thinned down at the smallest regions (B3 for tube T1 of Fig. 1a and B7 for tube T2 of Fig. 2a) through erosion by silicide and oxide particles of flue gases and fly-ash/ tube corrosion. The fly-ash corrosion is generally caused by the formation of complex alkali sulfates and acidic compound at the scale/metal interface, which are aggressive in nature [4, 5]. Accordingly, the hoop stress is generated at the thinned tube. The hoop stress ($\sigma_\theta = \frac{pd}{2t}$, where σ_θ is hoop stress, P is internal pressure, t is tube wall thickness and d is tube internal diameter) is about two times of the design strength (σ_t) of tube T1, as described in Table 3 on the basis of calculation from the thick (initial thickness) and thin regions of the failed tubes. Therefore, the hoop stress is operative in the thinnest regions when the tube wall is incapable to load carrying ability and at the extreme cases. However, the hoop stress generation is not prevalent in tube T2. The non-uniform heating acts as a leading role in the failure of tube T2, creating a non-linear temperature gradient along tube thickness, and causing the yielding at hotter side. It affects the distortion of tubes during the sequences of start up, in-operation and shut down [6], explained by a schematic diagram of Fig. 7. During operational period, the steam flows through the superheater tubes and picks up heat from flue gas flowing across the tubes. Accordingly, the tube temperature increases linearly from the inlet to the outlet, and the tube bows down to the cold side with no internal stress. The tube returns to its vertical position at shutdown period, and it is called in-plane distortion (Fig. 7a). In contrast, the non-linear heating sometimes leads to out of plane distortion in the superheater tubes, which occurs due to water condensation at some points of the circuits. It causes the non-uniform heat distribution in the tubes and generates higher internal stresses compared to the hot yield strength, resulting in the compressive yielding at hot side. Therefore, the bowed shaped tubes at the operation period bend down the opposite direction at the shutdown period (Fig. 7b). It corresponds to the generation of large nos. of voids and cracks in the grain boundaries, which is found in tube T2, and it accelerates the failure mechanism.

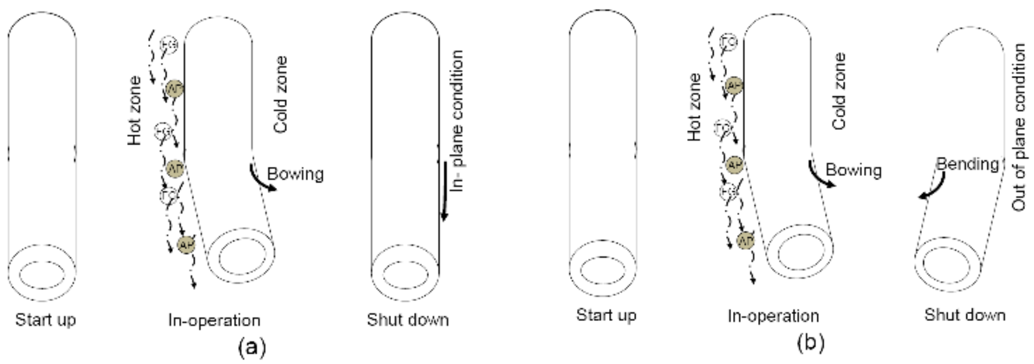


Fig.7 Tube conditions during start-up, in operation and shut down steps causing (a) in-plane distortion for linear heating, and (b) out of plane distortion in case of non-linear heating (FG: flue gas, AP: ash particles)

Certain coals contain constituents which form ash deposits that are molten at typical operating temperatures and can cause extensive corrosion. Therefore, periodical checking and removing of coal ash deposit from the tubes and the use of better quality coal are recommended to reduce such kind of failure. Moreover, the startup procedure is a consequence of gradual heating of tube for restricting the flue gas temperature and preventing the sudden water evaporation. The start up and shutdown procedure should be properly followed so that the non-linear heating does not take place, preventing the catastrophic failure within a short life time.

4. Conclusions

(a) Both superheater tubes are initially thinned down from outer surface by fly-ash corrosion, however, no material loss is taken place at the inner surface.

(b) In tube T-1, the excessive hoop stress generation at some points leads to catastrophic failure.

(c) In tube T-2, the non-linear heating is prevalent for catastrophic failure.

(d) Periodical checking and removal of coal/fly-ash deposit from the tubes and use of better quality coal is recommended to reduce outer surface thinning.

(e) The proper follow-up of start up and shutdown procedure may prevent the non-linear heating.

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